

Chapter 18

Life-Cycle Environmental Impacts of Biofuels and Co-products

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Abstract Issues of energy independence and security, global climate change, and the depletion of fossil resources drive research into biofuels and bioproducts. While emerging biofuels and biorefineries pursue lower carbon transportation fuels, careful consideration of a wide range of potential environmental impacts is necessary to avoid unintended consequences. These concerns can be addressed by holistic life-cycle evaluation of bioenergy/biofuel supply chains from raw materials acquisition, to fuel conversion and end use. Life cycle assessment (LCA) is a promising tool for assessing the environmental sustainability of these biofuels. This chapter discusses current biofeedstocks and fuels, introduces the methodological framework of LCA, and explores challenges, critiques, benefits, and applications of LCA in evaluating the environmental performance and sustainability of emergent biofuels and co-product systems. An analysis of algal biodiesel production is presented as a case study, and the broader implications and potential of LCA to inform decision making are explored.

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18.1 Introduction

Life cycle assessment (LCA) is a technique used to quantify the environmental impacts of a product or service that incorporates and aggregates the related resource consumption, emissions, and impacts across the various stages of the product's life. LCA has been touted as a relevant tool for assessing the environmental sustainability of emerging technologies, and has had significant application in the developing field of biofuels and bioproducts. LCA can be used to identify process inefficiencies and environmental “hotspots” along a supply chain; therefore, facilitating efficient eco-design, and helping support environmentally sound decision making. For these reasons, LCA is a germane and powerful tool for assessing emerging biofuel technologies. The goal of this chapter will be to present the challenges, benefits, and applications of LCA in evaluating biofuels and related coproducts. The chapter will include a discussion of current biofeedstocks/biofuels and provides a broad understanding of the methodological framework and role of LCA in evaluating the environmental performance and sustainability of emergent biofuels. The chapter is organized as follows: [Sect. 18.1](#) provides a basic description of the environmental, economic, and political motivation for biofuels. Additionally, [Sect. 18.1](#) compares different biomass types including first generation, second generation, and third generation feedstocks, and examines different conversion pathways to produce biofuels. [Section 18.2](#) presents a detailed description of the LCA framework and methodology, examines the application of LCA to biofuels, and reviews different environmental sustainability metrics. [Section 18.3](#) offers an overview of several previous biofuel LCA studies representative of 1st-, 2nd-, and 3rd-generation feedstocks and fuels, and also examines the challenges associated with the application of LCA methodologies to biofuels. A case study of algal biodiesel is provided in [Sect. 18.4](#). [Section 18.5](#) provides a summary of the chapter with consideration of the broader role of LCA in the development of sustainable fuels.

18.1.1 Political, Economic, and Environmental Motivations for Biofuels

The dawn of the twentieth century brought the rapid expansion and development of the petroleum, natural gas, and coal industries. Since then, the world's economies have become highly dependent on fossil resources to meet the demands of industry and to maintain consumer quality of life. Resultant depletion of fossil reserves has the potential to limit global economic growth, complicated by a current reliance on nonrenewable sources of energy that may threaten long-term global economic prosperity. In addition to these economic considerations, increased global demands for energy and transportation fuels as well as concerns

over global climate change have driven researchers to identify alternative liquid fuels which are more sustainable and carbon-neutral.

Accordingly, biofuels have gained widespread attention at academic, industrial, regulatory and political levels, and to some degree among the general public. Scientists have focused on identifying the most promising biofuel feedstocks and are investigating various biochemical and thermochemical conversion pathways to transform these feedstocks into useful fuel products. Research, development, and the subsequent commercial deployment of biofuels all have the potential to create new jobs and provide extensive economic benefits.

Rising atmospheric concentrations of anthropogenic carbon have become a mounting international concern as indicated by national and international responses to the work of the Intergovernmental Panel on Climate Change (IPCC 2007). A growing body of evidence suggests that increasing concentrations of greenhouse gases, brought on by human activities, are causing harmful and long-term global climate change, stimulating worldwide efforts for greenhouse gas (GHG) reductions. Since the transportation sector constitutes approximately 15 % of global GHG emissions (EPA 2010), displacing traditional transportation fuels with low-carbon or carbon-neutral biofuel alternatives presents one avenue for mitigating and stabilizing global atmospheric levels of anthropogenic carbon.

Policy makers are playing a larger role in the development and implementation of biofuels by establishing regulatory policies and mandates for renewable fuels. In 2007, the United States passed the Energy Independence and Security Act (EISA), which mandates annual domestic production targets for renewable transportation fuels. By the year 2022, production must reach 36 billion gallons including at least 21 billion gallons from cellulosic ethanol and advanced biofuels (Sissine 2007). Similarly, in 2008 the European Union (EU) passed the Renewable Energy Directive (RED), which mandates that 20 % of gross national energy consumption be derived from renewable sources by the year 2020 (Ismail and Rossi 2010). Additionally, in 2009 the EU passed a revised fuel quality directive (FQD) which requires transportation fuel suppliers to reduce life-cycle GHG emissions by 1 % each year culminating in a 10 % overall reduction by 2020. As has been discussed, technological, economic, and political factors will all play critical roles in the evolution and commercial viability of emergent biofuel industries.

18.1.2 Comparison of Potential Feedstocks, Fuels, and Conversion Pathways

Commercial biofuel production is a multifaceted issue: Identifying and assessing potential biofuel feedstocks remain an arduous process, as the use of some bio-feedstocks raises complex ethical questions and may have unintended economic and environmental ramifications. A myriad of different biofuel conversion

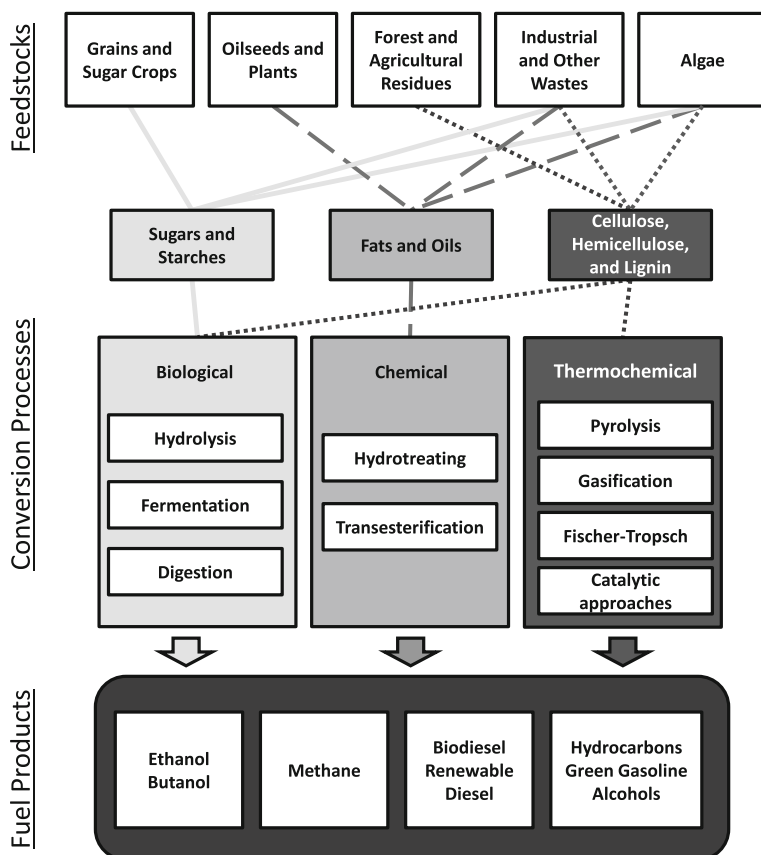


Fig. 18.1 Alternate biofuels production routes: feedstocks, conversion pathways, fuel products and coproducts

pathways and associated coproducts are possible, see Fig. 18.1. In addition, the mode of biofuel production can influence the quality of the resultant fuel as well as its related economic, environmental, and energetic impacts. This section will compare different biofeedstocks and examine different thermochemical and biochemical conversion pathways for producing biofuels.

18.1.2.1 First Generation Biofuels

First generation biofuels, also known as conventional biofuels, are derived from sugar, starch, animal fats, and plant or vegetable oils. Common first generation biofuels include: bioalcohols, bioethers, green diesel, vegetable oils, biogas, syn-gas, and solid biofuels (Naik et al. 2010). First generation biofuels are typically

produced from the fermentation of grains and crops with a high sugar or starch content, such as corn, sugarcane, sugar beets, wheat, or barley to produce bioethanol, or by transesterification of oils extracted from crops such as soybean, rapeseed, canola, mustard seed, palm, coconut, and sunflower to create biodiesel. Alternative biochemical pathways are being investigated for converting biomass into heat, electricity, or fuel utilizing a wide range of different technologies.

Despite the many advantages of first generation biofuels various economic, political, environmental, and social issues have hindered their widespread adoption. In recent years, political and scientific actors have raised concerns that the use of first generation biofuels may result in further environmental degradation (Pimentel et al. 2007), including potential loss of biodiversity, adverse impacts on water resources, soil erosion and depletion, accelerated deforestation, and land-use impacts (Sims et al. 2008).

Existing research has also reported that the direct and indirect land use change effects may possibly negate the carbon dioxide reduction potential of first generation biofuels resulting in overall higher life-cycle GHG emissions relative to baseline petroleum fuels (Fargione et al. 2008; Melillo et al. 2009; Searchinger et al. 2008). Additionally, thermodynamic and energy analyses have shown mixed results concerning the energetic balance of some first generation biofuels (Patzek 2004; Pimentel et al. 2007; Patzek and Pimentel 2005; Hammerschlag 2006).

Furthermore, without government subsidies and grants, biofuels are currently not cost competitive with more established transportation fuels (Pimentel et al. 2007), making them an expensive option for mitigating GHGs. Additionally, there is growing concern that displacing farmland and food crops for biofuel production may lead to inflation of global food prices (Timilsina et al. 2012; Nonhebel 2012; Pimentel et al. 2007), as many biofuel cultivars—including corn, soybean, and sugarcane—are primarily used for animal feed and/or human consumption. For these reasons researchers have investigated producing biofuels from alternative, nonfood crops.

18.1.2.2 Second Generation Biofuels

Many of the issues and shortcomings of first generation biofuels (*conventional biofuels*) are being addressed with second generation biofuels (*advanced biofuels*) (Eisentraut 2010; Sims et al. 2008). While first generation biofuels are generated from sugars, starch, and oils produced from arable crops, second generation biofuels are derived from forest and agricultural residues, lignocellulosic biomass, industrial wastes, and nonfood crop feedstocks. Second generation biofuels include: biomethanol, bioDME (DiMethyl Ether), biohydrogen, biomethane, butanol and isobutanol, DMF (2,5-DiMethylFuran), HTU (Hydro Thermal Upgrading) diesel, wood diesel, and mixed alcohols (Sims et al. 2010; Naik et al. 2010). Common biochemical pathways for second generation biofuels include the use of pretreatments, such as enzymes and microorganisms, to break down and extract the sugars contained in lignocellulosic biomass, which can then be

fermented to produce ethanol and other alcohols. Thermochemical pathways such as gasification, pyrolysis, and torrefaction of second generation biofeedstocks (Sheehan 2009) can be used to produce syngas of when bio-oil can be fermented or chemically reformed into various fuel products, including ethanol, synthetic diesel, or aviation fuel (Sims et al. 2008).

Despite their apparent advantage over first generation biofuels, second generation biofuels must overcome many technological and economic challenges before their commercial deployment (Williams et al. 2009). Development of these biofuels at a commercial scale has remained challenging, because many of these feedstocks cannot be produced all year long and can only be harvested periodically (Eisentraut 2010). Furthermore, second generation biofuels have also yet to prove cost competitive at a commercial scale. Improvements in biomass cultivation, processing, and conversion efficiencies will be crucial both to increasing biofuel performance and for cost reduction. While thermochemical conversion pathways commonly utilize mature, proven technologies to produce a wide range of synthetic fuels, current biochemical pathways are less technologically mature and may present greater potential for cost reduction through process improvements over time. Further, R&D will be required to optimize these conversion systems and to identify which thermochemical and biochemical conversion pathways are best suited for commercial-scale biofuel production.

18.1.2.3 Third Generation and Drop-In Replacement Biofuels

Third generation biofuels—fuels produced from microalgae (Dragone et al. 2010)—do not suffer from many of the major drawbacks associated with first or second generation biofuels, and in recent years have gained increased consideration as sustainable liquid-fuel alternatives. Microalgae are considered as an ideal feedstock for next generation biofuels due to their ability to be cultivated on nonarable land, high productivity (Chisti 2007), high lipid content, and semi-continuous to continuous cultivation and harvesting cycles. Microalgae have the potential to utilize wastewater, as well as CO₂ from industrial flue gas, for growth (Benemann 1997; Golueke CG 1965; Ho et al. 2011; Kadam 2001). Additionally, the production of microalgae needs not displace food, animal feed, and other arable-crop derived products. Microalgal derived fuels have the potential to act as “drop in” replacements for petroleum fuels since their chemical composition may prove compatible with the existing transportation fleets as well as current fuel storage and delivery infrastructure. Furthermore, researchers are exploring the application of modern technologies such as genetic modification to optimize the growth, resilience, and oil yield of new algal strains.

Open raceways ponds (ORP) and photo-bioreactors (PBR) are two standard growth configurations currently considered for the mass cultivation of microalgae (Jorquera et al. 2010). While PBR systems have better control over algae growth parameters, lower risk of contamination of the algal culture, and higher volumetric growth rates as compared to ORP, high capital and operating costs limit their

commercial potential (Xu et al. 2009). Due primarily to low capital costs, ORPs have gained increased consideration from industrial, governmental, and academic sectors. Between 1978 and 1996, the US Department of Energy's (DOE) aquatic species program studied algal biochemistry, strain selection, and the pilot-scale production of algal biodiesel using ORP systems (Benemann and Oswald 1996). More recent research has primarily focused on the production of algal biodiesel via transesterification and has identified CO₂ provisioning, fertilizer supply, and biomass drying as the primary rate-limiting factors in algae-to-fuel systems (Clarens et al. 2010; Kadam 2001; Lardon et al. 2009). A variety of cultivation, harvest, and conversion options have been examined (Brentner et al. 2011; Clarens et al. 2011; Soratana and Landis 2011) to produce multiple algal fuel and bio-energy products such as biomethane, renewable diesel, green aviation fuel (Agusdinata et al. 2011), and bioelectricity. Further research will be required to identify which cultivation, harvesting, conversion, and fuel-upgrading pathways are most energetically favorable and which are most economically and environmentally advantageous. A case analysis of algal biodiesel production is presented in Sect. 18.4.

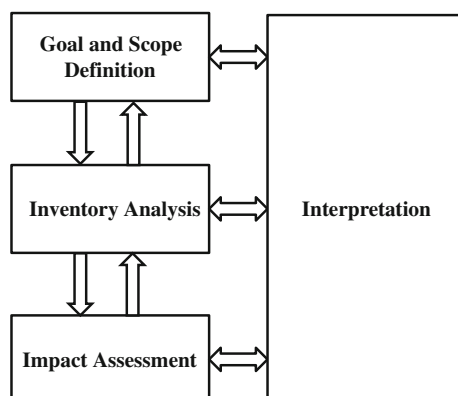
Understanding and assessing the far-reaching impacts and implications of emerging biofuels—before their widespread implementation—will be critical for assuring the long-term sustainability of these fuels. Failure to address the potential risks and impacts associated with biofuels may have long-standing environmental consequences, and may jeopardize the successful adoption and commercial viability of these bioresources. Comprehensive analysis from a systems perspective that consider the full range of environmental impacts can address these concerns. One widely popular systems analysis technique is LCA, which is discussed next.

18.2 LCA Methodology and Framework

18.2.1 LCA Approach

LCA is a systematic technique for quantifying and assessing the total environmental impacts of a product or process across all phases of the product's life cycle, as standardized in ISO 14040 (ISO 2006). The considered life cycle phases generally include: raw material extraction, input conversion, product manufacturing, packaging, transport, product use, and disposal or recycling at end of life. LCA's four distinct but interdependent steps are (1) Goal and scope definition, (2) Life Cycle Inventory (LCI) development, (3) Life Cycle Impact Assessment (LCIA), and (4) Interpretation and Improvement Analysis which are illustrated in Fig. 18.2.

Fig. 18.2 Life cycle assessment framework as standardized in ISO 14040



18.2.1.1 Goal and Scope Definition

The first step of performing an LCA includes defining the purpose of the study, its scope, and its context including the audience for whom it is intended. The temporal, spatial, and production chain boundaries of the system under study must be established, methods to be used identified, functional unit chosen, and impact categories of interest enumerated (Baumann and Tillman 2004). Purposes of LCA studies are often to compare products or to identify component processes responsible for the greatest contributions to life cycle environmental impacts. For example, the LCA might be designed to compare corn ethanol, soy biodiesel and their respective coproducts, or to analyze a single complete production pathway for the generation of bioelectricity from corn stover.

Boundary definition identifies what processes are included in the system to be modeled by the inventory analysis. This begins by setting the overall scope of the analysis in terms of the cycle life stages to include: from raw material extraction to capital equipment, from simple manufacturing to delivery, use and disposal. For example “cradle-to-grave” scope implies production, use and disposal phases, whereas “cradle-to-cradle” implies production, use and recycling. In fuel LCA, scope is often stated in alternate terminology relating to traditional petroleum fuel extraction processes: well-to-gate, well-to-pump, and well-to-wheels.

Defining the boundary is a balance between including too many of the connections to the greater economy (increasing work, time, and cost of the analysis) versus including too few component processes which could lead to incomplete or erroneous results. Restricting the scope of the study limits the extent of data collection, but also may limit the validity of results. Specific cutoff criteria for negligible contributions should be selected based on the percent contribution of an element to the total mass, energy, or environmental burden to the overall system.

The choice of a functional unit is more than setting a production quantity, it defines a fair basis for comparison and evaluation. It arises from the function of the product system, rather than the quantity of the product itself. Thus beverage packages (of varying sizes) may be evaluated not by bottle count, but by eight-ounce

servings delivered. Similarly, for fuel systems the functional unit may be defined in terms of gallon of ethanol equivalent (based on energy content), per megajoule (MJ) energy, person-kilometers traveled, or vehicle-kilometers traveled (VKT).

Among the important methodological considerations to be decided as part of the scoping process is the selection of allocation method. Allocation describes the method for splitting inventory flows and environmental impacts of a process across multiple coproducts produced in the examined system. Allocation and its ramifications will be discussed in greater depth below.

18.2.1.2 Life Cycle Inventory Analysis

The LCI analysis step consists of defining and quantifying all relevant flows of energy and materials into, through, and from the system (ISO 2006). Essentially, a flow model is built reflecting all the processes included within the system boundary including resource extraction, production processes, transport, use, and waste management. Input and output data are collected and documented for each process being modeled including flows of raw materials, energy, products and coproducts, wastes, and emissions to air and water. For cradle-to-grave studies, data collection is particularly extensive as it must include all upstream processes (resources extraction, production, and transport) as well as downstream processes (product use and disposal). While some process data may be available in public or commercial databases—such as Ecoinvent (Ecoinvent Centre 2007; Frischknecht 2005), GREET (ANL 2010), US LCI (Deru and NREL 2009), and ELCD (ELCD/ILCD 2012)—or through the use of software tools—including SimaPro (SimaPro 7.3.3/Pre Consultants 2012), GABI (GaBi 5/PE International 2012)—data collection can be resource and time intensive, especially when modeling site-specific processes and new technologies.

Once complete unit process data have been assembled, aggregate resource use and pollutant emissions can be calculated to determine environmental loads per functional unit for the overall system. The time-intensive process of assembling a complete LCI is complicated by processes that produce more than one product. In this case, shares of the inventory must be assigned to each coproduct through the allocation procedure(s) selected during the goal and scope phase.

18.2.1.3 Life-Cycle Impact Assessment

The purpose of LCIA is to translate the resource and emissions flows identified in the LCI into their potential consequences for the environment and human health. It consists of a two-step process of impact classification and quantitative characterization. The classification step links each LCI flow with its respective impacts on resource use, human health, and the environment (ISO 2006).

The characterization step calculates the magnitude of the associated impacts in terms of a reference unit for each category. For example, though carbon dioxide,

methane, and nitrous oxide each have different strengths as GHGs, their global warming potential (GWP) can be measured and aggregated in the common unit of CO₂ equivalents. Specifically, 1 kg methane has a global warming impact equivalent to 25 kg of CO₂ and 1 kg nitrous oxide has a global warming impact equivalent to 298 kg of CO₂ (IPCC: M.L. Parry 2007; IPCC: B. Metz 2007). Therefore, the GWP characterization factors for methane and nitrous oxide, relative to CO₂, are 25 and 298, respectively. These factors enable the LCA practitioner to aggregate the GWP impacts from these disparate substances into one combined measure. Similar characterization factors for a vast number of chemical substances and impact categories are available in the literature and through public and commercial databases.

This process of classifying, characterizing, and aggregating related results into a series of midpoint indicators, which summarizes each type of life-cycle environmental impacts, facilitating the comparison of complex systems. Normalization of impact categories allows for the comparison of tradeoffs between different environmental impacts. A midpoint impact assessment method developed by the US Environmental Protection Agency (EPA), the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) translates the environmental loads identified by the life-cycle inventory into 11 specific impact categories: ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, ecotoxicity, human health criteria-related effects, human health cancer effects, human health noncancer effects, fossil fuel depletion, and land-use effects (Bare et al. 2003). Alternative midpoint assessment methods include: ReCiPe (Goedkoop et al. 2009), USEtox (Querini et al. 2011; Rosenbaum et al. 2008), CML 2001, EDIP 2003 (Dreyer et al. 2003), Ecological scarcity 2006 (Frischknecht et al. 2009), Greenhouse Gas Protocol (Ranganathan et al. 2004; Sundin and Ranganathan 2002), Ecological footprint (Huijbregts et al. 2008).

Additional weighting and normalization steps may be used to further aggregate midpoint indicators into endpoint or damage indicators such as ReCiPe (Goedkoop et al. 2009), Eco-indicator 99 (Dreyer et al. 2003), Impact 2002+ (Jolliet et al. 2003), and EPS 2000. The various LCA tools have been evaluated extensively in the literature (Landis and Theis 2008; Kulkarni et al. 2005; Dreyer et al. 2003; Olsen et al. 2001; Whittaker et al. 2011). While single metrics may conveniently summarize damages to human health and the environment, facilitating interpretation by decision makers, the LCA practitioner's choice of end-point valuation scheme is subjective and controversial, and is often skipped in favor of a midpoint analysis. The chosen LCIA approach should correspond with the goal and scope of the study.

18.2.1.4 Interpretation

During the interpretation phase of the LCA process, the process is evaluated and validated, conclusions are drawn from the preceding LCI and LCIA, and recommendations made based on inventory and impact assessment data. In addition, the

interpretation phase should include the validation of results, and can often lead to iterative revisions to and improvements in the other LCA phases. Validation of the results is essential and may include analysis of variability and uncertainty in the model using a variety of qualitative sensitivity analysis techniques as well as quantitative statistical procedures. As the LCA process requires, the aggregation of data from multiple processes with varying degrees of uncertainty, statistical techniques offer the most robust treatment for uncertainty in the assessment.

Conclusions may include the identification of the product or process with lowest impact(s) or identification of specific subprocesses of greatest impact, so-called “hot spots” which can then be targeted for improvement, enabling businesses to both increase product quality and reduce harmful environmental impacts.

18.2.1.5 Attributional versus Consequential LCA

LCA models may also differ in the approach employed to address the material and energy flows in the system under investigation. The attributional LCA (ALCA) methodology, which has been utilized for a vast majority of biofuel LCA studies, attempts to quantify the flow of resources and emissions from a product system and its subsystems. Emissions and their related impacts are attributed to the final product by one of several available methods, including allocation strategies, and system expansion. ALCA determines the magnitude of environmental burdens which can be attributed to a product or service, and which processes within the production chain account for the greatest share of impacts. Researchers have argued that it is not fully possible to draw conclusions on future changes by using only ALCA (Ekvall and Weidema 2004; Schmidt 2008; Weidema et al. 1999).

In contrast, consequential LCA (CLCA) methodology, aims to explain how the physical flows to and from the technosphere may change in response to a change in the life cycle of the product or service. CLCAs attempt to consider a much broader system boundary. The most commonly employed form of a CLCA considers the use of economic models. These models track monetary, material, and energy flows across economic systems. In a CLCA, the consequential effects of production are added within the system as resources enter or leave the economic market, thereby changing the supply–demand dynamics, and potentially causing changes in resource use and associated environmental impacts. In other words, the system under investigation is expanded to include the consequences due to changing some production patterns outside the narrowly defined life cycle of interest. This is generally accomplished using marginal data and is accounted for on the basis of price elasticities of supply and demand (Lesage et al. 2007; Lund et al. 2010; Reinhard and Zah 2009; Sanden and Karlstrom 2007). Such change-oriented LCAs focus on the broader environmental impacts of alternate courses of action, such as the replacement of the existing technologies with a new technical option. For example, in an algae-to-biodiesel consequential LCA, the main desired product is the biofuel. However, the production of glycerol as a byproduct may result in the replacement of glycerol production via other methods involving greater

consumption of nonrenewable resources. Similarly, the coproduction of animal feed may displace other sources of animal feed existing in the market. As with any attempt to predict the future, CLCA faces inherent challenges due to data and modeling limitations as well as inherent uncertainty.

18.2.1.6 The LCA Approach—Challenges and Benefits

LCA studies have been criticized for various reasons including (1) incomplete or obsolete process LCI data, (2) inappropriate system boundaries, (3) poor allocation procedures, or incomplete accounting for byproducts. The assumption that emissions can be scaled linearly may not correspond to processes that exhibit a range of emissions, depending on scale or temperature or other factors. Also LCA results may either not be generalizable beyond the specific geographic location and time period of the analysis, or they may include process data that are outdated or inappropriate to the specific location. The specific application of LCA to fuel systems is discussed below and further in the case study in [Sect. 18.4](#).

18.2.2 LCA and Fuels

LCA methodologies are increasingly essential to evaluating the sustainability of both traditional and alternative fuel products. Many life-cycle studies of biofuels concentrate primarily on energy analysis and greenhouse gas emissions, though other impacts such as water consumption, eutrophication potential, and land-use change are of increasing interest. This section will present the major components and metrics of life-cycle energy analysis as well as a discussion of life-cycle GHG analysis.

18.2.2.1 Major Energy Metrics

A variety of metrics are used to quantify the consumption of primary energy in the production of biofuels (Murphy et al. [2011b](#); Cleveland [2010](#); Chwalowski [1996](#)). In contrast to the process energy used directly in a given process, primary energy represents the total of all energy resources consumed to produce the materials and energy used in the process. For example, operating a 40 W light bulb for 1 h would use 40 W-hours of process energy (electricity), while the total primary fuels consumed to generate and transmit that required electricity would be on the order of 108 W-hours (assuming a primary energy factor of 2.7) with wide variability due to specific geographic location, technologies, and above all the specific mix of primary fuels used to generate the electricity.

Several principle energy metrics are defined and summarized in [Table 18.1](#). One key measure considered for biofuels is the net energy balance (NEB) also

Table 18.1 Key energy metrics

Name	Abbreviation	Formal definition
Net energy balance	NEB	$\sum \text{Energy}_{\text{output}} - \sum \text{Energy}_{\text{input}}$
Energy return on investment	EROI	$\frac{\sum \text{Energy Output}}{\sum \text{Energy Input}}$
Net energy ratio	NER	$\frac{\sum \text{Energy Output}}{\sum \text{Energy Input}}$
Fossil energy ratio	FER	$\frac{\sum \text{Energy Output}}{\sum \text{Fossil Energy Input}}$
Energy breeding factor	BF _{en}	$\frac{\sum \text{Energy Output}}{\sum \text{Nonrenewable Energy Input}}$

known as net energy value (NEV). NEB is defined as the difference between the energy in the biofuel product (and coproducts) and the total primary energy required to produce the fuel. A positive net energy balance is one criterion for sustainable fuel product. The energy return on investment (EROI) and net energy ratio (NER) represent ratios of the total energy in the biofuel product and its coproducts to the total primary energy required to produce them. NER values greater than one correspond to a positive energy balance.

A variation of energy return on investment, fossil energy ratio (FER) considers only the consumption of nonrenewable fossil fuel resources and is defined as the ratio of the sum of energy content of the products over the primary fossil fuel inputs consumed during production. This metric considers only the nonrenewable fossil fuel components of primary energy and serves to evaluate how much of fuel product is generated per unit investment of fossil fuels. FER values greater than 1 are net fossil energy positive, reflecting more energy in the products than the fossil energy consumed during production. Thus, FER is a measure of the renewability of the fuel. The energy breeding factor, an analogous metric, represents the energetic return per unit of nonrenewable energy consumed.

18.2.2.2 Criticisms of Energy Metrics

Net energy balance and related metrics have been criticized for aggregating different types of energy with no adjustment for their differing quality or value (Murphy et al. 2011a; Liska et al. 2009; Liska and Cassman 2008; Murphy et al. 2011b; Dale 2007). The implicit assumption that all energy carriers are equal and can be added together is contradicted by the observed wide variation between energy carrier prices. Compare, for example, the per million BTU prices for the following fuels: \$2/mmBTU for coal, \$10/mmBTU for petroleum, and \$24/mmBTU for electricity. These fuels are clearly valued not just for their energy content, but for the services that they can provide, that is the differing utility or usefulness of coal, petroleum, and electricity (Dale 2007). Despite their intuitive appeal, ratios that assume all energy forms are fungible can be at best of only limited value. The choice of energy metrics must be informed by a clear

understanding of the goal(s) of the analysis. If the policy goal is to increase domestic energy security policy-driven metrics such as petroleum displacement ratio or FER should be considered. If the goal is to reduce GHG emissions to increase climate security, metrics such as GHG emissions per vehicle-kilometer traveled are more appropriate (Dale 2007).

A recent study proposed a set of nine complementary energy metrics for comparing biofuel systems. These metrics span three categories of evaluation (Lavigne and Powers 2007)

- energy consumption (from fossil, petroleum, and renewable sources)
- energy security (NEV, %foreign consumed, and % domestic consumed), and
- energy resource consumption (% renewable consumed, energy efficiency ratio, and net energy resources for transportation)

In general, a move toward the use of more transparent and holistic methodologies for the evaluation of biofuels can better reflect the multiple energy, environmental, economic, and security goals.

18.2.2.3 Greenhouse Gas Emissions and LCA

Concerns over the specter of global climate change have resulted in international and national legislation designed to limit the release of GHGs throughout national economies, particularly from the transportation sector. As a result, reduction of GHG emissions has arisen as one of the primary drivers for the biofuels industry. In the United States context, the current renewable fuel standard (RFS2) requires the production and blending of renewable fuels into the US fuel mix. RFS2 requires reductions in life-cycle GHG emissions of these renewable fuels as compared to the petroleum fuels they replace. For example, advanced biofuels must achieve at least a 50 % reduction in GHG emissions across their life cycle (EPA 2010).

A first step in modeling GHG emissions is to execute a carbon balance, that is, to determine the flows of carbon into, through, and out of the production system. The LCA practitioner must be cognizant of the biogenic and anthropogenic sources of elemental carbon moving through the cultivation, fuel production, and combustion chain. While petroleum fuel combustion releases “new” atoms of carbon into the atmosphere that had previously been stored in underground formations over geologic timescales, biofuel combustion does not necessarily release “new” CO₂. Atmospheric CO₂ which is fixed into plant biomass via photosynthesis, converted to fuel, and returned to the atmosphere during fuel combustion, does not result in the addition of any new—that is anthropogenic—atmospheric carbon dioxide, and therefore has no impact on global warming.

Carbon accounting can become problematic when comparing studies with different system boundaries. For example, a study of biomass cultivation might indicate that atmospheric carbon is fixed by photosynthesis, and therefore “sequestered” in the biomass product, potentially resulting in net negative GHG

emissions. A second study of biomass cultivation and conversion may show that the same biogenic carbon is again embedded between two coproducts, fuel and residual biomass. While biofuel combustion *per se* may be carbon neutral, the fate of the carbon embedded in the coproduct must also be considered. For example, while residual biomass used as a soil amendment may sequester carbon in the earth for several years, residual biomass combusted for the generation of bioelectricity results in immediate release of the fixed carbon resulting in no true sequestration. A well-to-wheel LCA of the complete biofuel cultivation, production, and combustion system also requires the consideration of both direct and indirect life-cycle emissions of all GHGs including methane, nitrous oxide, and CFCs and anthropogenic CO₂. Additionally, the choice of allocation method can have a strong impact on the LCA results.

18.2.2.4 Allocation and Coproducts

For an integrated system that produces more than one product, system expansion and allocation are alternative techniques for allowing the resource consumption and emissions to be equitably split between the coproducts. System expansion refers to expanding the conceptual boundary of the studied system, such that it is credited for emissions avoided from another system. That is, the primary system (S1) generating primary product (P1) and coproduct (P2) is credited in an amount equivalent to the avoided emissions; that is, the emissions which would have been generated had P2 been produced in its own virgin system (S2).

According to ISO 14040, when allocation cannot be avoided by using system expansion or increasing the detail of the model, it should split environmental loads among the system's "different products or functions in a way which reflects the underlying physical relationships between them" (ISO 2006). Relevant physical relationships may include mass, volume, and energy content. When a physical basis for allocation cannot be determined, it should be based on another relation between the coproducts, such as their proportional economic value. Additionally, ISO 14040 requires a sensitivity analysis to be carried out when multiple allocation procedures are possible. As different allocation methods can yield widely varying LCA results (Kaufman et al. 2010; Azapagica and Cliftb 1999; Luo et al. 2009), this variability can be captured and effectively communicated through a sensitivity analysis.

Beyond allocation, issues of coproducts scale may also arise. An almost trivial case occurs when the production of the coproduct exceeds that of the primary product either in terms of mass or value. An alternative case particularly suited to the study of biofuels and other nascent industries occurs when the scale of production increases to industrial scale to meet the growing demand for the primary product. Concurrent coproduct production may surpass its own market demand. This could result in dramatic drops in market price for the coproduct to the point where any additional marginal production must be treated as waste.

18.3 Biofuels LCA: Selected Applications

This section provides an overview of several previous LCA biofuel studies including an updated report on the life-cycle performance of corn ethanol, soybean diesel, and a comparison of algal bioenergy to other 1st- and 2nd- generation biofuels. Issues and challenges with previous biofuel studies are addressed.

18.3.1 *Corn Ethanol*

The rapid expansion of the US ethanol industry over recent years has brought about significant advancements in biomass harvesting, processing, and conversion technologies, resulting in a plentitude of corn-ethanol studies (Hill et al. 2006; Farrell et al. 2006; Hsu et al. 2010; Kendall and Chang 2009; Kim et al. 2009; Kim and Dale 2005, 2008; Patzek 2004; Patzek and Pimentel 2005; Pimentel et al. 2007). These technological improvements and process efficiencies have had a significant impact on the environmental and energetic performance of corn ethanol. Liska et al. (2009) examined the impacts of technological maturation and system evolution on the life-cycle energy efficiency and GHG emissions of corn ethanol. The life-cycle energy efficiency and GHG emissions for various corn-ethanol systems were evaluated utilizing updated values for crop yields and agricultural management, bio-refinery operations, and coproduct utilization, which were compared against prior studies based on older process technologies. The results indicate that corn ethanol has the potential for 48–59 % GHG reduction as compared to traditional gasoline, approximately 2–3 times greater than previously reported values. Additionally, ethanol-to-petroleum output-to-input ratios were found to range from 10:1 to 13:1. It was hypothesized that a ratio of 19:1 could be achieved if farmers adopted alternative agricultural and soil management practices. The net energy ratio (NER) of corn ethanol was determined to range from 1.5 to 1.8, significantly higher than prior reported values of approximately 1.2. The authors also considered corn ethanol production utilizing a closed-loop bio-refinery coupled with an anaerobic digestion system. Under this scenario the NER was found to be 2.2 coupled with a 67 % reduction in GHG emissions. The conclusions of this study highlight the importance of technological maturation and ongoing innovation in emerging bioenergy systems, and reveal that corn ethanol's updated environmental and energetic performance is competitive with projected values for cellulosic-ethanol and other advanced biofuels.

18.3.2 *Soy Biodiesel*

In 1998, the US National Renewable Energy Laboratory (NREL) conducted the first complete energetic LCA of US soy biodiesel (Sheehan et al. 1998). This landmark study constructed an energy inventory for soy biodiesel based on 1990

agricultural data. This analysis was updated in both 2009 and 2011 to reflect technological improvements in soybean farming, processing, and biodiesel conversion, utilizing agricultural data from 2002 to 2006, respectively. In the most recent analysis, Pradhan et al. (2011) compared the updated energetic performance of soy biodiesel against the two prior studies, and discussed the influence of technological development and agricultural advancements on life-cycle inventories and related energy balances. The findings indicate that the Fossil Energy Ratio (FER) for soy biodiesel has substantially increased over time: from 3.2 in the 1998 NREL report, to 4.56 in the 2009 study, and finally to 5.54 in the 2011 report. The authors attribute this gradual increase in FER to increased soybean yields, improvements in soybean crushing, and advancements in biodiesel conversion operations. The results indicate reductions in energetic inputs (normalized per unit volume of biodiesel) for agricultural operations, soybean crushing, and transesterification of 52, 58, and 33 %, respectively, as compared to the 2002 report. The authors partially attribute the reductions in the energetic inputs for agricultural operations to a decrease in pesticide use resulting from the recent adoption of genetically engineered (GE) soybeans. Additionally, reductions in the energy consumption in biomass conversion and processing are largely attributed to increased efficiency and optimization of the soybean crushing and transesterification facilities and operations. These conclusions suggest that continued advancements in the agricultural sector and in the biofuels industry will allow for further optimization of the biofuel supply chain, leading to potentially lower biofuel production costs and increased biofuel FER values over time.

18.3.3 Algae-Derived Bioenergy

In recent years, microalgae have received substantial interest as a potentially sustainable source of bioenergy. While microalgae derived fuels do not exhibit many of the drawbacks of first generation or advanced biofuels, recent studies have indicated that third generation biofuels may exhibit high upstream energetic and environmental impacts. Researchers have suggested that industrial symbiosis, such as the use of industrial flue gas and wastewater effluent in algae cultivation, as well as alternative production scenarios, such as the production of biomethane via anaerobic digestion of algal biomass, may alleviate concerns over algae's environmental performance (Soratana et al. 2012; Borkowski et al. 2012; Vasudevan et al. 2012; Edward et al. 2012; Campbell et al. 2011; Collet et al. 2011; Murphy and Allen 2011; Yang et al. 2011; Singh and Olsen 2011; Brentner et al. 2011; Sander and Murthy 2010; Ferrell and Sarisky-Reed 2010; Batan et al. 2010; Sialve et al. 2009; Huesemann and Benemann 2009; Chisti 2008). In a 2011 study, Clarens et al. performed a well-to-wheel LCA of algae-derived biofuel and bioelectricity and compared the results against other biofuels (Clarens et al. 2011). In this study, multiple algal nutrient provisioning, harvesting, and conversion scenarios were modeled. Algae's performance was then evaluated against other biofuel feedstocks

in terms of equivalent VKT normalized per hectare of cultivated land. The results reveal high dependence of the energetic balance and environmental performance of algal energy systems on the mode of bioenergy production. The direct combustion of algal biomass for bioelectricity outperformed scenarios involving anaerobic digestion or algal biodiesel production, yielding a maximum EROI of approximately 4.92. Additionally, scenarios involving the direct combustion of algal biomass generally produced higher VKT than either switchgrass or canola. Given the large variability in algae's energetic and environmental performance, careful consideration of the algae-to-energy supply chain is required to ensure the long-term sustainability of emerging algal bioenergy systems.

18.3.4 Issues and Challenges to LCA of Biofuels

Biofuel LCAs often examine different system boundaries, utilize diverse functional units, and present results using a host of various sustainability and energy metrics. This creates difficulties in comparison between studies. Because LCA is becoming an increasingly prevalent tool for informing environmental and political decision-making progress toward a unified and standardized LCA framework for assessing biofuels and their associated coproducts is crucial. Factors such as coproduct allocation and substitutability, model assumptions, and data quality can highly influence LCA results for biofuels.

Another key issue with biofuel LCA is addressing uncertainty and variability (McKone et al. 2011). Common methods for assessing uncertainty and variability include both the use of Monte Carlo simulations to determine model uncertainty based on known or assumed underlying probability distributions, and the One-Factor-At-a-Time (OFAT) method in which input parameters are varied separately to determine their relative influence on the LCA results. However, these methods can be time- and resource-intensive, and may be constrained by issues of data quality and availability. Additionally, due to data averaging and the assumption of linear relationships, traditional LCA models of resource use and emissions generation cannot fully capture the effects of spatial (Yazan et al. 2011) and temporal variation, nor do they account for industrial dynamics and technological change. Similarly, the spatial (Yazan et al. 2011), temporal, and dynamic complexities of environmental response are not fully captured by traditional LCA.

Although sustainability indicators such as life-cycle GHG emissions and energy consumption are commonly studied in biofuel LCA, examination of the entire range of environmental impact categories is necessary for comprehensive understanding and to avoid unintended shifting of environmental burdens from one impact category to another. Furthermore, no generally accepted impact categories or standard methodology exist for reporting direct and indirect water consumption or land use, which are important issues meriting further study. The complexities of applying LCA methodologies to biofuels are illustrated in the following brief case study of algal biodiesel.

18.4 Case Study: LCA of Algal Biodiesel

A comparative well-to-pump LCA was conducted to investigate the life-cycle GHG emissions and FER of algal biodiesel derived from algae cultivated in open raceway ponds. Comprehensive evaluation of production pathways allows for a greater understanding of the potential tradeoffs, environmental impacts, and technical practicality of different algae production options. Additionally, prior algal biofuel LCAs have shown mixed results regarding algae's environmental and energetic performance, often as a consequence of differences in system boundaries and model assumptions. Holistic evaluation of multiple algal biofuel production pathways within the framework and assumptions of one study can address these issues.

18.4.1 Methodology

This study examines the production of algal biodiesel produced via transesterification and the effects of varying the use of the residual biomass coproduct. The system boundary begins with the cultivation of algal biomass and extends to the delivered fuel product, capital costs for cultivation, extraction, and fuel conversion were excluded. As the ultimate fuel product was to be combusted in the existing vehicle fleets, combustion processes were assumed to be equivalent to those used for the existing petroleum fuels and were excluded from this analysis (Huo et al. 2008). The functional unit of this study was chosen as one megajoule (MJ) of biodiesel at pump, allowing easy comparison with petroleum diesel. It was assumed that biomass cultivation and fuel production would occur in an integrated open raceway pond biorefinery located in Phoenix, Arizona, and would be co-located with an industrial source of waste flue gas. The biofuel production chain is shown in Fig. 18.3, which illustrates the major subsystems: cultivation, primary and secondary harvest, drying, oil extraction, fuel upgrading, and three alternate use-pathways for the residual biomass.

The extraction subsystem model was developed using data from the Ecoinvent database (Ecoinvent Centre 2007), initially on a per-pound-of-oil-extract basis, which was subsequently scaled to the per-MJ-fuel functional unit. Biodiesel requires approximately 1 lb. bio-oil per lb. of output. For mature processes such as oil extraction life-cycle data are readily available from the peer review literature as well as databases including GREET (ANL 2010), Ecoinvent (Ecoinvent Centre 2007), and USLCI database (Deru and NREL 2009).

Data for molecular composition of the de-oiled biomass were based on Lardon et al. (2009) and data on energy density and molecular composition of algal and soy meals came from the 2011 GREET model (ANL 2010). The use of waste industrial flue gas was modeled as a source of CO₂ (Benemann 1997). Algae were assumed to be grown under nitrogen deprivation conditions to maximize lipid

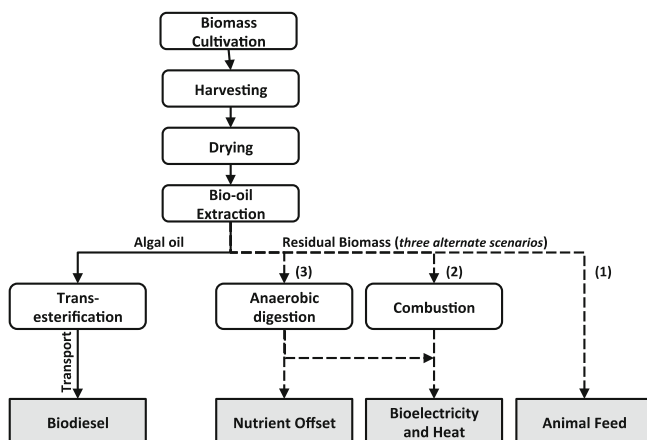


Fig. 18.3 System diagram for production of algal biodiesel and coproducts

content while reducing the requirement for synthetic fertilizers (Cho et al. 2011; Converti et al. 2009; Illman et al. 2000). The resultant algal biomass was modeled using a mean fractional composition of 38.5 % lipids, 52.9 % carbohydrates, and 6.7 % proteins. Biodiesel can be produced only from the lipid fraction of the biomass, leaving the remaining 60 % as a coproduct or as waste. This study considers several alternative uses for the residual de-oiled algal biomass (DOAB), including as an animal feed product (modeled through the displacement of soy-meal feed); as a combustion fuel for the creation for bioelectricity and heat; and as a feedstock for anaerobic digestion, which produces bioelectricity, heat, and recycled nutrients.

18.4.2 Results

For allocation purposes in the animal feed scenario, DOAB molecular composition was compared with that of soybean meal and soy beans to develop displacement ratios based on the protein content of each. Additional information and extended results can be found in a related study published in the proceedings of the 2012 IEEE-ISSST (Borkowski et al. 2012).

Primary fossil energy use across the component processes of the algal biofuel production system is indicated as inputs for three separate scenarios in Fig. 18.4. The corresponding outputs column for each scenario shows one MJ of produced biodiesel fuel product, along with any proportional coproducts. The largest contributions to primary fossil energy consumption arise from heating processes involved in biomass drying and biooil extraction, followed by electricity used in harvesting, cultivation, and oil extraction.

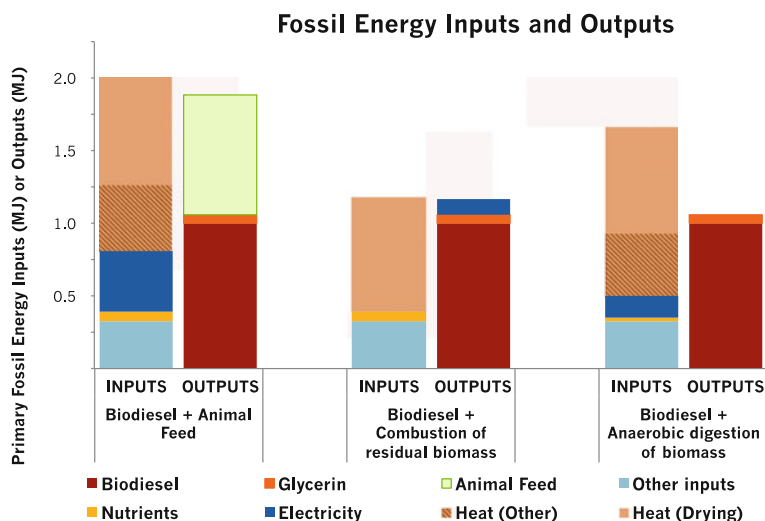


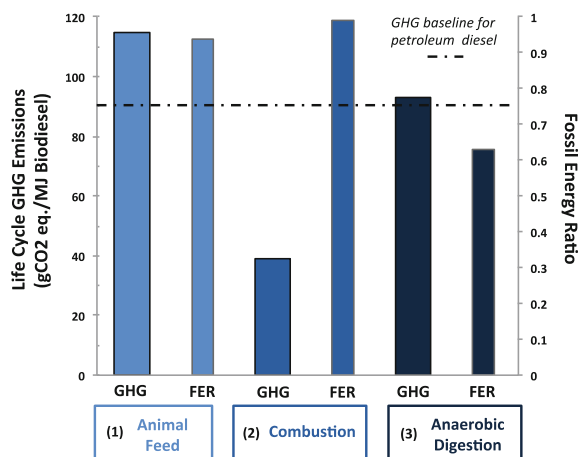
Fig. 18.4 Fossil energy inputs and outputs normalized per MJ biodiesel

Comparing the baseline animal feed scenario to that where the residual biomass is combusted for heat and power, we see a 42 % decrease in net fossil fuel consumption as well as the generation of approximately 0.1 MJ surplus bioelectricity per MJ of biofuel produced. The anaerobic digestion case shows smaller reductions in heat and electricity consumption, no surplus of bioelectricity, as well as a reduction in synthetic fertilizer consumption due to nutrient recycling. These three alternate scenarios may be more easily compared by examining the ratio of outputs to fossil energy inputs, that is, via the FER values as summarized in Fig. 18.5. The residual biomass combustion shows the highest FER value of 0.99, followed by the animal feed scenario (FER: 0.94), and by the anaerobic digestion scenario, which exhibits the lowest FER value of 0.63.

The modeled GHG emissions do not directly correspond to FER results as can be seen in Fig. 18.5. The anaerobic digestion scenario shows GHG emissions of 93 g of CO₂ equivalent per megajoule, which is on par with those of petroleum-derived diesel. The animal feed scenario shows emissions of 115 g CO₂ eq/MJ, which is higher than the petroleum diesel benchmark. The lowest GHG emissions correspond to the biomass combustion scenario with 39 g CO₂ eq/MJ, in which the greatest avoidance of electricity and natural gas consumption is achieved.

Given that under 40 % of the cultivated biomass is lipids (oils) by weight, the variation in GHG emission levels and FER values between scenarios is not surprising. The fate of the residual biomass coproduct, representing the majority 62 % of the mass, clearly has significant effect on LCA results. Comparing the anaerobic digestion and animal feed scenarios shows a clear example of the trade-offs revealed by LCA, while the anaerobic digestion scenario exhibits lower (*better*) GHG emissions than the animal feed case, it also exhibits lower FER, that is,

Fig. 18.5 Life-cycle GHG emissions and fossil energy ratio of biodiesel production under various residual biomass scenarios



worse energetic performance. The combustion scenario is most attractive with both lower GHG emissions and highest FER results.

Though the purpose of a given study may be to examine the environmental impacts of the biofuel products, an accurate LCA must consider the complete system including all coproducts as well as the inevitable trade-offs between different impact goals. Considering the high variability in the energetic and environmental performance of algal biodiesel in just the three coproduct scenarios studied here, LCA clearly offers the potential to evaluate the multiplicity of alternative feedstocks and production pathways discussed in Sect. 18.1 and to inform the sustainable development of nascent algal biofuel industries.

18.5 Conclusions: The Broader Role of LCA in the Development of Sustainable Biofuels

As discussed earlier, the adoption of biofuels/bioenergy has the potential to decrease dependence on foreign oil, reduce consumption of nonrenewable resources, mitigate GHG emissions and global climate change, and boost the domestic economy. Holistic evaluation of various biofuel supply chains from a life cycle perspective can help to indicate the degree to which these objectives are met. Additionally, given the multitude of potential biofeedstocks and biofuel conversion pathways, LCA represents a useful tool both for comparing environmental sustainability among pathways and for guiding the sustainable development of biofuel industries. Policy makers are adopting life cycle thinking and LCA metrics into renewable fuel regulation and legislation. Scientists are using systems analysis, such as LCA, to identify process inefficiencies and hotspots for targeted improvement along myriad possible biofuel supply chains.

While LCA is increasingly valued by researchers, practitioners, and decision makers, it currently faces multiple methodological challenges. These include issues of data quality, uncertainty, system boundaries, spatial and temporal data resolution, scale, and system dynamics as well as trade-offs inherent to optimizing competing goals. To address these issues, researchers are developing increasingly sophisticated models and metrics. New tools for analyzing geo-spatial and regional/localized impacts are helping to quantify impacts on local watersheds and to disentangle the complexities of indirect land-use change. Issues of data quality and availability are being met with the development of commercial and private databases. Some of the shortcomings of traditional LCA are being met with alternative forms of LCA such as Economic Input Output Life Cycle Assessment (EIO-LCA), Ecologically based Life Cycle Assessment (Eco-LCA) (Baral et al. 2012), and hybrid approaches (You et al. 2012; Acquaye et al. 2011).

By insisting on an LCA “seal of approval”, or seeking a single reductive metric to answer the complex questions of sustainability, decision makers fail to utilize the true potential of LCA (McKone et al. 2011). LCA can best serve the nascent biofuels industry when it remains an iterative process, much like the scientific method itself. Iterative LCA has the potential to coevolve with technology while providing the basis for adaptive planning through an ongoing symbiotic collaboration among the LCA practitioner, the basic scientist, the R&D community, and decision makers in industry, finance, and government. Vital roles exist for

- Scientists and engineers in research and technology development—targeting hot-spots for process improvement, emission reduction, and efficiency improvement
- LCA practitioners—identifying areas of uncertainty and variability, posing new questions, and driving the coevolution of LCA models with new technology
- Decision makers—organizing information, resolving conflicting goals, and working to understand aggregated impacts while gaining a deeper understanding of the underlying issues, risks, and potential benefits of the studied system and broader ramifications across its life cycle.

Building on the common basis of life cycle thinking, LCA models and methodologies can guide the development of emergent biofuels industries onto a path that is simultaneously economically viable, energetically efficient, and environmentally responsible.

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